Sensitivity limits of atom interferometry gravity gradiometers and strainmeters

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Outline

• AI sensors, state of the art performance
• Main noise sources
• Potential improvements
• Technology readiness of AI sensors for field use
Atom interferometry

Initial state $|\psi_i\rangle$

path I amplitude $A_I$

Final state $|\psi_f\rangle$

path II amplitude $A_{II}$

Interference of de Broglie amplitudes

Light-pulse beam splitters + fluorescence detection

Output phase selectively sensitive to different effects (inertial, gravitational, external fields, laser phase/frequency, etc) via choice of quantum states
AI & low frequency GW

- AI inertial sensors feature very good long term stability and control over systematic effects
  - might provide complementary technologies for <Hz GW detectors
- Gravity gradiometers
  - measurement/correction of NN
- Strain meters
  - free fall: vibration isolation without suspensions
  - quantum interaction of light with test mass
    - no radiation pressure noise
    - vertical orientation
- Rotation sensors
Current performance

• Gravimeters
  • resolution: $3 \times 10^{-9}$ g in 1 second (SYRTE)
  • averaging down to $2 \times 10^{-10}$ g after 30 min (SYRTE)
  • accuracy: $10^{-9} \div 10^{-10}$ g, limited by tidal models
    • P. Gillot et al., Metrologia 51, L15 (2014)

• Gravity gradiometers
  • differential acceleration sensitivity: $5 \times 10^{-9}$ g in 1 s
  • $5 \times 10^{-11}$ g after $10^4$ s

• Rotation sensors
  • sensitivity: $6 \times 10^{-10}$ rad/s/√Hz
  • scale factor stability <5 ppm
  • bias stability <70 µdeg/h
Sensitivity limits

- Quantum noise
- Acceleration noise
- Laser wavefront
- Atomic motion
- Laser phase and frequency noise
- Aliasing
- External fields
- Other technical noise sources
- NN
Quantum projection noise

Phase difference between the paths:
\[ \Delta \Phi = k_e [z(0) - 2z(T) + z(1T)] + \Phi_e \]
\[ k_e = k_1 - k_2 \]
with \( z(t) = -\frac{gt^2}{2} + v_0 t + z_0 \) \& \( \Phi_e = 0 \)
\[ \rightarrow \Delta \Phi = k_e gT^2 \]

Final population:
\[ N_a = \frac{N}{2} (1 + \cos[\Delta \Phi]) \]

\( T = 150 \text{ ms} \rightarrow 2\pi = 10^{-6} \text{ g} \)
\( S/N=1000 \rightarrow \text{Sensitivity } 10^{-9} \text{ g/shot} \)
Acceleration noise

\[ \Delta \Phi = k_\varepsilon g T^2 \]

- \( T = 5 \text{ ms} \), resolution = \( 2.3 \times 10^{-5} g/\text{shot} \)
- \( T = 50 \text{ ms} \), resolution = \( 1.0 \times 10^{-6} g/\text{shot} \)
- \( T = 150 \text{ ms} \), resolution = \( 3.2 \times 10^{-8} g/\text{shot} \)

Up to 140 dB CMRR with 1 m separation

Atomic motion

- AI phase is affected by residual atomic motion
- Velocity spread due to finite temperature
- Shot to shot jitter in initial position and mean velocity
- Atomic motion couples with
  - Laser wavefront distribution
  - Coriolis acceleration & higher order inertial effects
  - Gravitational and magnetic gradients
- Coupled constraints on atomic temperature, launching velocity, and wavefront jitter
- Limits are particularly stringent for very long baseline (space GW detectors)
- For ground applications, nK temperatures and lambda/100 wavefront errors would be ok
Laser frequency noise

- Simultaneous AI sensors (gradiometer, strain meter) sharing the same atom optics provide excellent CMRR for phase noise of laser field.
- However, for long baseline the differential measurement is affected by common mode laser frequency noise due to high propagation delay.
- Requirements on laser frequency noise are dramatically released if the beam splitters are driven by one-photon transitions (e.g. Sr clock transition @ 689 nm)
  - P. W. Graham et al., PRL 171102 (2013)

\[ \sigma^2 \sim 4 \frac{\pi^4}{\tau} \frac{d^2}{c^2} S_N \]
Bandwidth & aliasing

- Sensitivity $\sim T^2$
- Bandwidth $\sim T^{-1}$
- Highly sensitive gravimeters detect earthquakes
  - $T \sim 50$ ms
  - rep rate $\sim 5$ Hz
- Improving $T$ without loosing bandwidth
  - interleaved interferometers
  - main limit: Doppler separation of different channels
- see e.g. I. Dutta et al., PRL 116, 183003 (2016)

Technical noise sources

- magnetic fields
- stray light
- photon shot noise
- tilt noise

Potential improvements

\[ \Delta \Phi = n k g T^2 \]

- Large momentum transfer splitters (increase \( n k \))
- Large scale Al (increase \( T \))
- High flux atomic sources (reduce quantum noise)
- Choice of atomic species
- Interferometer topology
- Squeezing
Large momentum transfer

- H. Müller et al., PRL 102, 240403 (2009)
- S.-W. Chiow et al., PRL 107, 130403 (2011)
- G. D. McDonald et al., PRA 88, 053620 (2013)
Long interaction time

• Microgravity: in principle $T > 10 \text{ s}$
• Increasing $T$ on Earth
  • trapped atoms (Sr)
    • up to 15000 coherent photon recoils
    • decoherence time $>500 \text{ s}$
      • G. Ferrari et al., PRL 97, 060402 (2006)
      • V. V. Ivanov et al., PRL 100, 043602 (2008)
      • M. Tarallo et al., PRA 86, 033615 (2012)

• free fall
  • requires large vertical size
  • requires very low temperatures (~nK): good for LMT splitter
  • 10 m atomic fountains already operating: Stanford, Wuhan
    • T. Kovachy et al., Nature 528, 530 (2015)
  • next future: Hannover, Firenze
  • expected differential acceleration noise $\sim 10^{-13} \text{ g/shot}$

Sensitivity limits…
Multiple samples

- Use three atomic clouds to measure the vertical derivative of vertical gravity gradient
- Scalable to arbitrary large number of samples
- Simultaneous, correlated AI can improve g measurements as well
- Multiple, correlated AIs to mitigate NN

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See talk by S. Pelisson
Atomic species

- Most sensitive AI have been realised with alkali atoms (Rb, Cs)
  - Simple laser cooling
  - Splitter based on Raman transitions between hyperfine states -> simple detection of AI output ports
- Some interferometric schemes would work better with other species (e.g. Sr)
  - low sensitivity to stray fields
  - fast cooling to sub-μK temperatures
  - intercombination lines allow single-photon splitters to reduce the effect of laser frequency noise with long $T$
Squeezing

TRAPPED IONS
[1] Sackett et al., 2000  NIST
[3] Leibfried et al., 2003  NIST
[4] Leibfried et al., 2004  NIST
[5] Leibfried et al., 2005  NIST
[15] Monz et al., 2011  Innsbruck
[19] Noguchi et al., 2012  Tokyo
[27] Bohnet et al., 2015  NIST

BOSE-EINSTEIN CONDENSATES
[6] Esteve et al., 2008  Heidelberg
[10] Reidel et al., 2010  Basel
[16] Lucke et al., 2011  Hannover
[17] Hamley et al., 2012  GeorgiaTech
[20] Berrada et al., 2013  Wien
[21] Okeleone et al., 2013  Basel
[23] Strobel et al., 2014  Heidelberg
[25] Muessel et al., 2015  Heidelberg

COLD ATOMS
[7] Appel et al., 2009  Copenhagen
[8] Leroux et al., 2010a  MIT
[9] Schleier-Smith et al., 2010  MIT
[12] Leroux et al., 2010b  MIT
[13] Louchet-Chauvet et al., 2010  Copenhagen
[14] Chen et al., 2011  JILA
[18] Sewell et al., 2012  IFCO
[22] Bohnet et al., 2014  JILA
[26] Barontini et al., 2015  ENS
[28] Hosten et al., 2016  Stanford
[29] Cox et al., 2016  JILA

Sensitivity limits...
Summary

- Differential acceleration sensitivity of a ~10 m size vertical gradiometer
  - interaction time $T$
  - $n$ photon recoils
  - $10^6$ atoms at QPN
- $n=30$, $T=1.5$ s $\rightarrow$ $6\times10^{-13}$ g
- $n=100$, $T=3$ s $\rightarrow$ $4\times10^{-14}$ g

- Vertical strainmeter made of two samples with separation $L$

\[ h_{rms} = \frac{1}{2nkL\sin^2(\omega T/2)\sqrt{\eta}} \]
Technology readiness

• Commercial atomic gravimeters & gradiometers
  • MuQuans (France)
  • AOSense (USA)
  • AtomSensors (Italy)

• Prototypes for microgravity
  • I.C.E. (CNES)
  • QUANTUS/MAIUS (DLR)
  • S.A.I. (ESA)


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Thank you